# Flexible Modeling and Simulation for Mass Customization Manufacturing

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## Abstract

Mass Customization Manufacturing (MCM) systems possess special characteristics that make the modeling of such systems extremely difficult. These characteristics include concurrency, synchronization, and cooperation among subsystems. To support the development and analysis of these systems, new approaches to modeling and simulation must be developed. In this paper, an architecture for a modeling and simulation platform to support MCM is presented. The platform can represent solutions to problems such as dynamic rescheduling, shop reconfiguration, and multi-robot cooperation and coordination.

## Keywords

mass customization manufacturing, system modeling, petri net, multi-robot cooperation and coordination

## 1. Introduction

Today, competition in the dynamic global market place has pushed manufacturers to consider the strategic orientation toward mass customization manufacturing (MCM), to provide customized products and deliver them rapidly while keeping costs down. Developing strategies that allow manufacturers to implement and reap the benefits of MCM is a big challenge.

For complex products such as automobiles or aircraft, the manufacturing system plays an important role in enabling MCM. Adopting MCM implies the ability to dynamically reconfigure available manufacturing resources to execute the right production processes to produce any possible product. This coincides with what Andrew calls a network process environment[1]. Because establishing a new production line requires a considerable investment, the existing line has to be able to produce a huge number of different variants, often with unequal capacity requirements. Significant imbalances can occur that may prevent an efficient or even a feasible execution of the processes. Adaptable production systems and coordinated production control programs must be designed to enable factories to be flexible enough to combat these problems. Bock indicated that the adaptive assembly line becomes crucial to support an efficient production control[2]. Smirnov also said that on-line re-planning appears as a “must have” feature of commercial manufacturing planners[3].

When compared with conventional manufacturing systems, the highly flexible manufacturing systems needed for MCM have three special requirements[4]:

1. The software for production planning, process planning, and process control must be nimble and re-configurable.
2. The layout of manufacturing system must support rapid reconfiguration according to process plans for the changed product or an aggregated new module for advanced technology.
3. The scaling of production to support varying lot sizes must be agile and seamless.

Planning such revolutionary production lines requires significantly more analysis than for conventional lines. Unexpected production conditions must be handled. Efficient line balancing and utilization of robots are crucial for enterprises employing MCM to reach their financial goals and recoup their capital investments. To address these problems, new technologies must be developed. Among them, a basic and critical one is the development of a platform for flexible modeling and simulation to support Mass Customization Manufacturing.

## 2. Modeling And Simulation Platform Architecture For MCM

The platform is an integrated collection of applications employing modeling, simulation, and analytic technologies. It enables enhanced simulation and optimization of the manufacturing scheme, allows decision and control at all process levels, and reduces product development time and production cost. Using this platform, the problems of manufacturing system modeling, factory/workshop design, process analysis, system integrated control, and robotic control can be studied. This platform can help manufacturers shave time and costs from the production process by allowing engineers throughout the enterprise to create, analyze, visualize and simulate factory layout and materials flow, optimizing line balance and finally reaching the goals of MCM. The platform is composed of model development subsystem, simulation and analysis subsystem, and control development subsystem, as depicted in a figure 1.

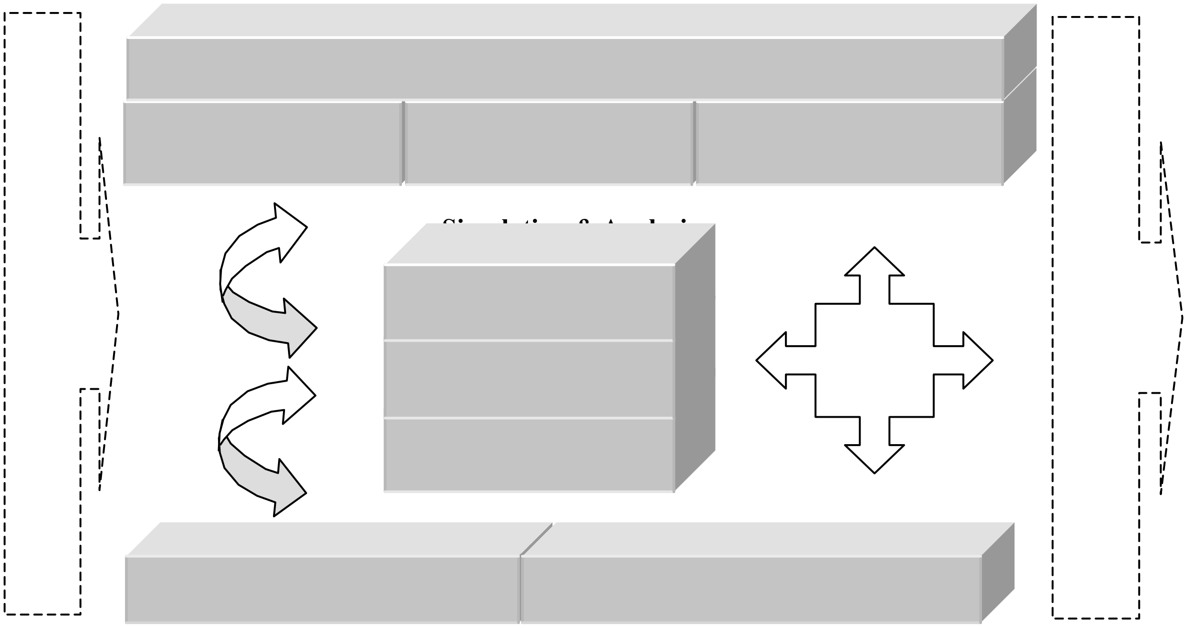


Figure 1. Modeling and simulation platform architecture for MCM

The model development subsystem is the lowest and the most basic level of the platform where we establish the geometry and kinematics model for robots and other devices in their environments. Using these models, the simulation and analysis subsystem can analyze the workshop design, dynamically simulate and optimize the manufacturing process, estimate the capability of manufacturing and propose a new reconfiguration of the system to satisfy the customer's new demands. The robot simulation subsystem will help in resolving kinematics problems, checking movement path and simulating the process, while collision detection is being performed. The highest level is the control development subsystem, which deals with the problems of process control, multi-robot cooperation and coordination, and unpredictable case handling,, including error recovery. A petri net embedded process control methodology is employed to allow reconfiguration of the process when necessary. Multi-robot cooperation and coordination analysis is important when more than one robot is working in the same production line, and the line needs to be re-adjusted to adapt to a new manufacturing task. Because MCM confronts unpredictable environments, unexpected production conditions including machine breakdown must also be handled.

## 3 Model Development Subsystem

To support simulation and analysis of all aspects of a factory, geometry models of all of the physical elements of the factory must be created in the computer. A compound, discrete-modeling methodology of constructive solid geometry (CSG) and boundary representations (B-Rep) is employed because large numbers of calculations are needed in inverse kinematics calculation and collision detection. CSG methodology is used to construct primitive components (including cube, prism, pyramid, cylinder, cone, ring, and sphere). Complex components are created from primitive components using Boolean operations. B-Rep methodology is used to describe objects with surfaces, including information about the geometry (the exact parameters of faces, edges, and points) and the topology (the relationship of points, edges, faces, and their influence scopes) of the object. Thus three-dimensional bodies are represented as wire frame, surface, and solid models.

Kinematics modeling is used to establish the kinematics operation of a robot. The modeling process can be described as follows: 1) Establish joint linkage (including father and son bar, joint types, and joint position); 2) Establish the coordinate frame for each joint, based on primary parameters; 3) Denavit-Hartenberg (DH) parameters calculation; 4) Construct an orientation matrix for each joint.

## 4 Collision Detection In The Simulation And Analysis Subsystem

For MCM, the production line is frequently reconfigured. To ensure the process can be carried out safely, collision detection analysis must be applied. The manufacturing environment is composed of thousands of objects including robots, machines, tools, and all kinds of devices. If no algorithm were adapted properly, it would be difficult work even for just the first step, to detect the possibility of collision between pairs of objects. Moreover, since a robot is multi-articulated, although each arm can be thought of as a convex polyhedron, yet the entire robot is indeed a concave polyhedron. Thus the collision detection problem in a multi-robot production environment is converted to a real-time, dynamic, collision detection problem with multiple concave polyhedrons, multiple moving objects, and complex obstacles. It is a challenging algorithm, which demands high efficiency, simplicity, reactivity, and reliability.

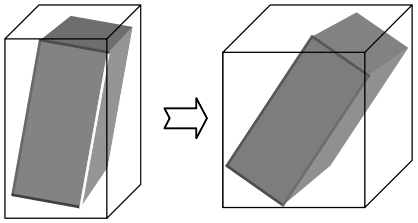
A hierarchical, closed-fixed bounding box algorithm is put forward based on the compound geometry model. The algorithm can automatically determine the exact and forthcoming geometry contact, and detect the nearest Euclidian distance between two moving objects, which is extremely useful in penalty function calculations during motion planning.

As described in figure 2, traditional axis-aligned bounding boxes are easy to generate, but there can be large amount of misjudges during collision detection analysis. Therefore, closed-fixed bounding boxes are introduced to avoid this shortcoming. Closed-fixed bounding boxes remain closely fitted to the shapes of objects they envelop, even as those objects change their positions in space. But it is very hard and complex to regenerate such closed-fixed bounding boxes. We can generate an axis-aligned bounding box for each object when it is created at the object origin. This axis-aligned bounding box is stored as a part of the geometry model. Since an object's orientation can be changed through transformation and rotation matrix calculations, the bounding box can then follow the object closely by doing the same matrix calculations, thus simplifying the calculation of bounding box regeneration. A closed-fixed bounding is convex and extends outside of the object by a scalable value to enable the detection of a collision ahead of the actual collision occurrence.

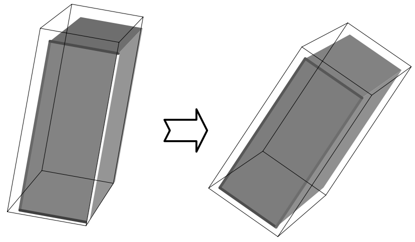
Before collision detection is performed, modeling conversion is performed to get the hierarchical, closed-fixed bounding box representation as depicted in figure 3. Mechanisms are defined as objects with articulations whose entire bounding boxes are compounded by convex bounding boxes of sub-mechanisms. The bounding boxes of sub-mechanisms can be continuously broken down to the level of convex bounding boxes of elements. Robots are special kind of mechanisms where collision detection is needed in their own sub-mechanism level to prevent the arm of a robot from colliding with its own body. Pair-wise collision detection is carried out top-down using a separating axis algorithm[5] to filter the non-interferential object pairs. For those pairs that might collide, a Voronoi Region Algorithm [6] is employed to trace the closed features and calculate the closest distances of interference.

## 5. Flexible Control System Modeling Using Valid Petri Net

MCM systems must possess capabilities that are not required by other manufacturing systems, including support for flexible assignment of resources and alternative routings for parts. The modeling method used for MCM systems must be flexible enough to support the dynamic modification of schedule information and material handling requirements. Moreover, the incorporation of new workshop configurations due to unexpected events such as machine breakdowns or part rework must be supported.



a) Axis-aligned bounding box



b) Closed-fixed bounding box

Figure 2. Two types of bounding boxes

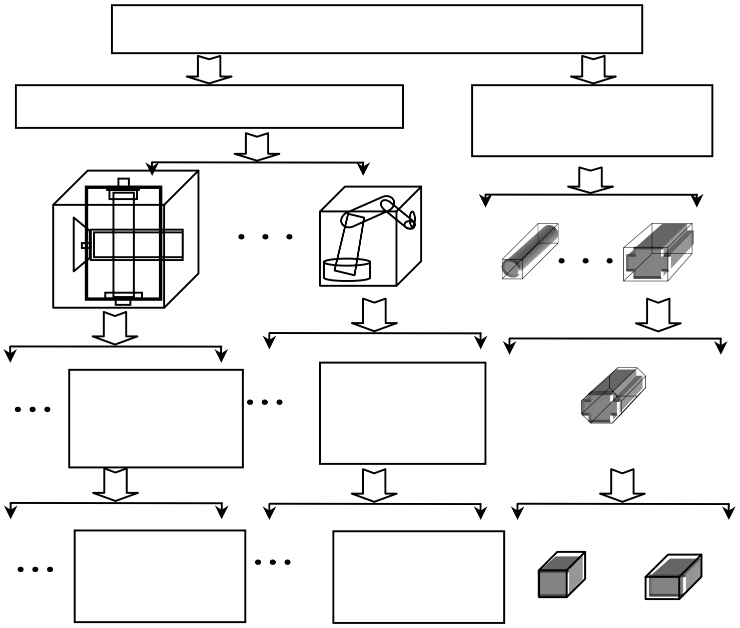


Figure 3. Bounding boxes structure

To support the modeling of MCM systems, an efficient, colored-valid petri net (PN) modeling methodology has been developed [7]. It offers not only a means to model discrete-event systems graphically and mathematically, where concurrence, synchronization, and cooperation exist among subsystems, but also models can be easily converted into control programs. It is critical to guarantee that the PN models being developed are valid, which means the model is reliable, without overflow, deadlock, or conflicts. The validity of a PN model is defined by three properties:

1. Bounded, which indicates the absence of overflow in the system model. This characteristic allows the specification of a limit on the number of tokens that may be in a place at any time.
2. Live, which implies that there is no possibility of deadlock.
3. Reversible, which indicates that the system can return to its initial state from any current state. This characteristic is very important for error recovery.

The PN valid extension theorem is utilized here[8]. (See reference 8 for the theorem and its proof). It states that, if valid PN models are combined in accordance with the connection rules, then the entire combined PN model is valid. According to its theorem, first, a set of valid PN models of basic serial/parallel systems, buffers and shared recourses are set up. A complex manufacturing system can be broken down into different functional cells described by these valid PN models. Rearrangement and insertion of new functional modules is easily accomplished by using the Petri Net valid extension theorem.

Based on this modeling methodology, highly flexible, rapidly re-configurable production lines can be designed in detail and analyzed using simulation tools. Manufacturing processes can be planned and optimized. Factory layout can be simulated. Moreover, if demand changes, the simulation model can be quickly modified to perform analysis according to the new demand. Based on this analysis, manufacturing capability and production process can be adjusted, layout can be reconfigured, and resources can be reassigned. A flexible modeling approach such as this is needed to support MCM, which emphasizes dynamically and seamlessly adjusting current production to customer demand without interrupting current production activities.

## 6 Multi-robot Cooperation And Coordination

Automating factory operations through the installation of robotic systems represents a major capital expense that must be utilized as much as possible to create returns on investments. One scheme for maximizing robot utilization is to continuously assign work to each robot according to its capacity and availability through a control system. For a multi-robot system, the control scheme is more complex because it has two problems to solve when each robot attempts to accomplish its tasks. The first problem is robot cooperation, which deals with decomposing complex tasks into simpler tasks and appropriately assigning these simpler tasks to each robot in the system to accomplish the complex task cooperatively. The second problem is robot coordination, which involves having robots available to execute tasks at the appropriate time so that cooperation can take place.

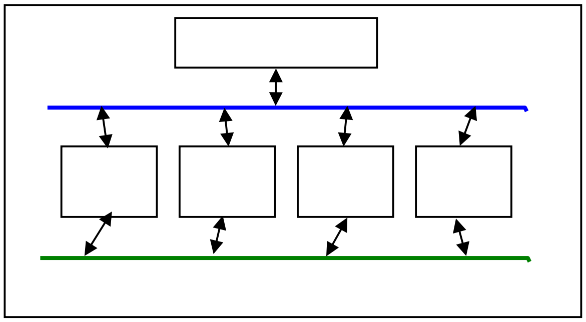


Figure 4. A multiple robot system overview

Figure 4 provides an overview of a multiple robot system, where the system controller handles the task assignment to each robot. Figure 5 further describes the operation of a robot cell, where the robot cell controller handles the coordination of tasks assigned. To increase the mass manufacturing efficiency, communications among robots may take place through the robot remote I/O lines instead of the high traffic system Ethernet lines.

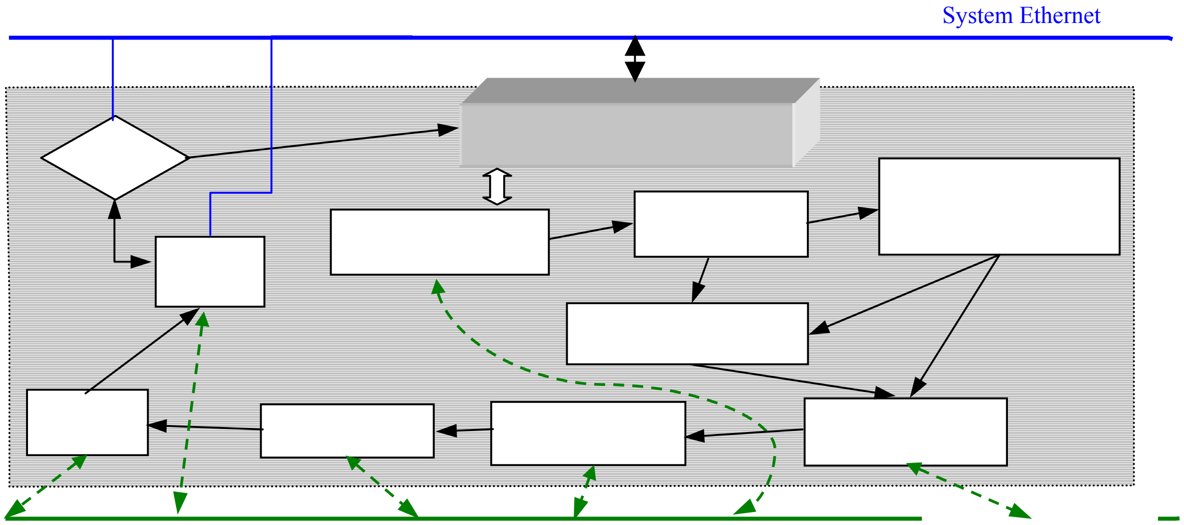


Figure 5. A flexible robot cell control scheme

To ensure multi-robot coordination, an event-based task-coordination strategy is presented below.

1. Each robot cell controller continuously receives task assignments from the system controller. The robot cell controller then decomposes tasks into individual operating steps in a queue. The controller in each robot executes in a fashion such that the final state of the current task is connected with the initial state of the next task. Then all actions will be executed continuously.
2. Each robot cell controller reports its status to the system controller on a fixed timeframe, like a heartbeat health indicator. The cell controller can also inquire and be informed of statuses of other robots.
3. A robot must apply for the right to incorporate a new task into the current plan. Only one robot is permitted to obtain the right at a given time.

The task coordination strategy produces a virtual global plan, which is a coordinated task plan of all robot cells. If robot cells perform according to the global plan, their operations are guaranteed to be coordinated. The task coordinate strategy can be outlined as follows:

1. Gather the coordinate plans from other robot cell controllers.
2. Apply for the right to perform the first insert of a new task into existing sequence.

3. If the right is granted from system controller, the new task can be inserted.
4. Time constraints may be introduced upon entering a new operation sequence into the current task plan of the robot cell.
5. When the time constraints are reached, the robot cell controller coordinates with its system controller to decide whether to continue or wait for further instructions.

It is not guaranteed that the task can be successfully added into the global plan. If the task assigned from the system controller is beyond the capability of the robot or cannot be coordinated with other robot tasks, the robot cell controller sends information upstream and waits until a new task is assigned.

This algorithm of each controller allows the system to react to dynamic and unpredicted events rapidly.

## 7. Conclusions

The ability to do mass customization manufacturing will change current manufacturing methods. MCM is changing the way consumers are making purchases. It will also have a strong impact on how products are made. To provide the mass customized products while keeping the prices competitive, adaptive flexible manufacturing methodologies have to be developed. In this paper, an architecture for a modeling and simulation platform is studied to support MCM.

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## References

1. Andrew, B. C., Bart, V., and Pine, B J, 1993, “New Competitive Strategies: Challenges to Organizations and Information Technology”, IBM System Journal, 32(1), 40-64.
2. Bock, S., 1999, “A New Model for Planning Complex Assembly Lines in Support of Efficient Mass Customization”, Proceedings of selected papers of the Symposium on Operations Research, 473-479.
3. Smirnov, Y., 1999, “Manufacturing Planning Under Uncertainty and Incomplete Information”, At the "Planning under Uncertainty" section of the AAAI Spring Symposium, Stanford. <http://www-2.cs.cmu.edu/afs/cs/user/smir/www/papers/papers.html> (18 December 2002)
4. Sheng, B.H., Yu, S. M., 1998, “The Principle and Application of Rapid Reconfigurable Manufacturing System”, Proceedings of 17th BMTRI-FANUC technology Workshops, Oshino-mura, October, Yamanashi, Japan, 1-12.
5. Gottschalk, S., 1996, “Separating Axis Theorem. Technical Report TR96-024”, Department of Computer Science. University of North Carolina, Chapel Hill, 20-46.
6. Cohen, J., Lin, M., 1995, “I-collide: An Interactive and Exact Collision Detection System for Large-scale Environments”, Proc. of ACM Interactive 3D Graphics Conference, 189-196.
7. Qiao, G., McLean, C., Riddick, F., 2002, “Simulation System Modeling for Mass Customization Manufacturing”, Proceedings of the 2002 Winter Simulation Conference. December 8-11, San Diego, California.
8. Zhou, M. C., DiCesare, F., 1991, “Parallel and Sequential Mutual Exclusions for Petri Net Modeling of Manufacturing Systems with Shared Resources”, IEEE Trans. on Robotics and Automation, 7(4), 515-527.